Coherent electron Cooling (CeC) PoP experiment

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Project physicist: Igor Pinayev
Project theory: Gang Wang
Project Engineer for CeC team: Joseph Tuozzolo

- Status of CeC PoP experiment
- Risk mitigation: alternative hadron cooling method

eRHIC R&D Cost and Effort Estimate Review
August 2015

BROOKHAVEN NATIONAL LABORATORY
a passion for discovery

eRHIC requires strong hadron cooling:
Ultimate requirement < 1 min cooling time @ 250 GeV

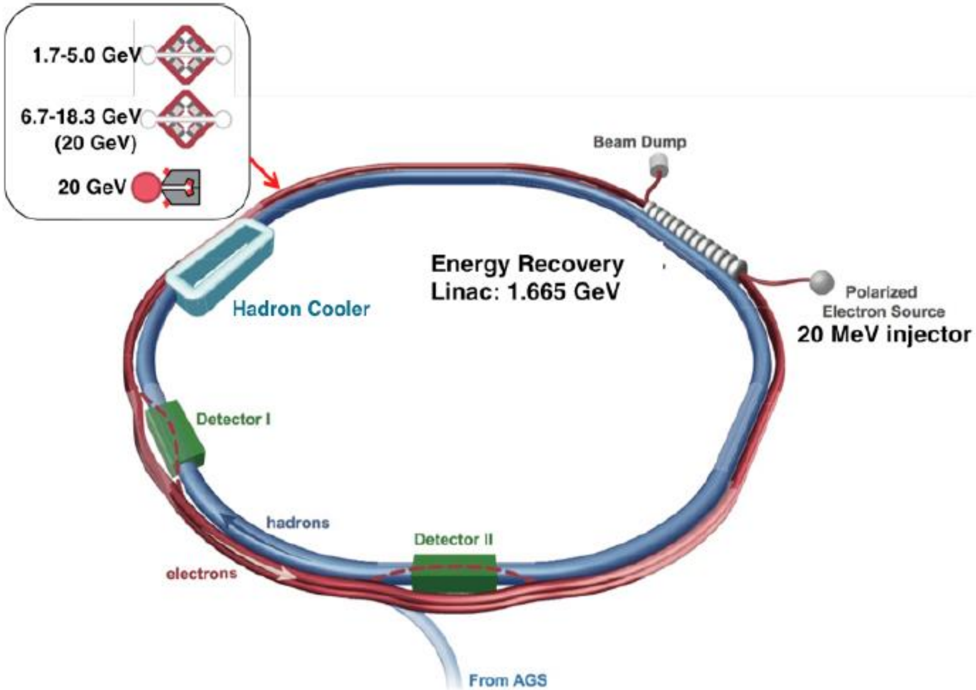
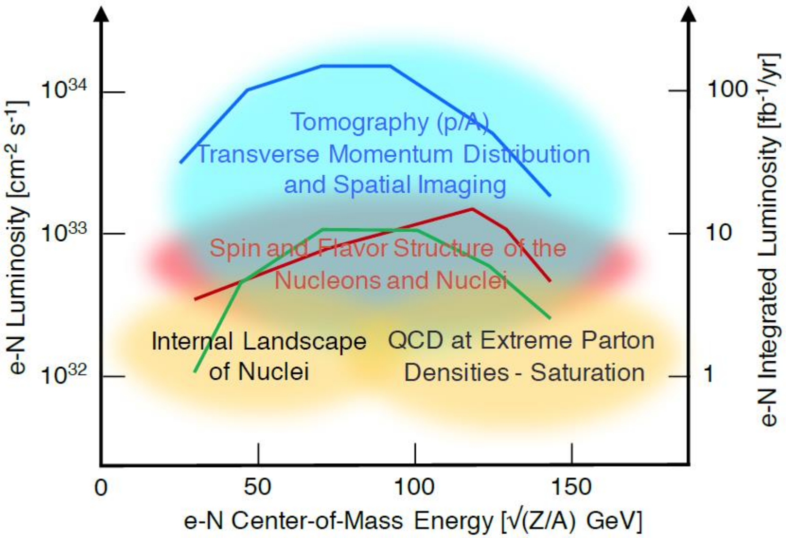


Figure 2-1: The layout of the eRHIC collider.



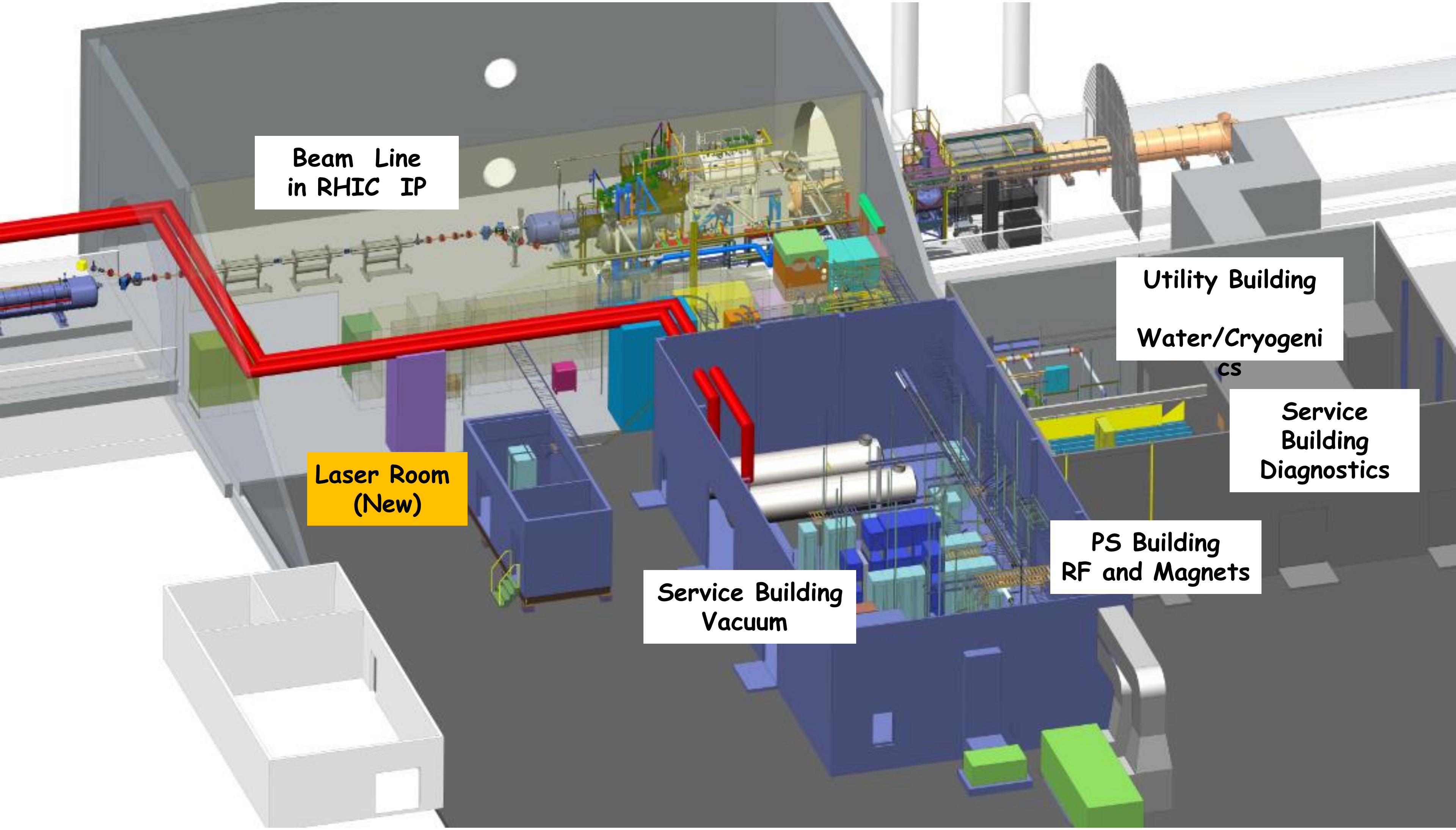
Blue curve: ultimate LR design

Green curve: nominal LR design

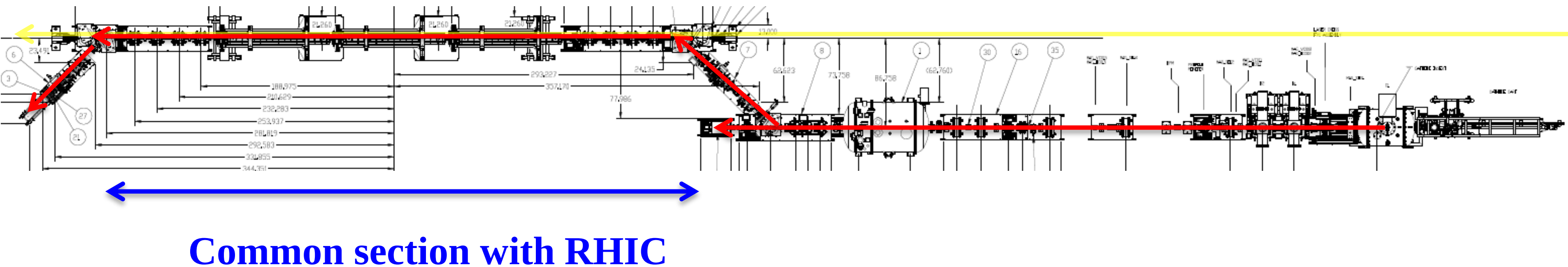
Red curve: nominal RR design

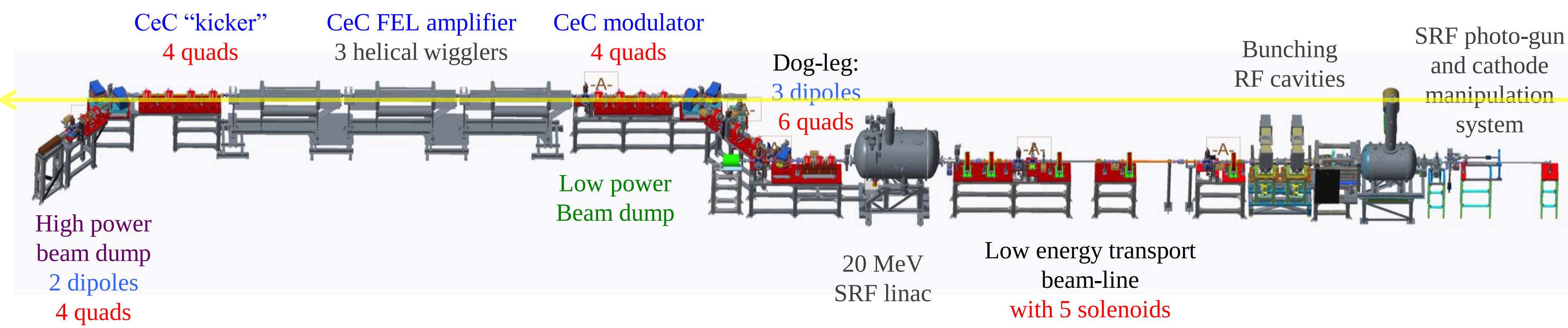
Coherent electron Cooling is needed to achieve the ultimate luminosity and has to be tested -> CeC PoP

CeC Proof-of-Principle Experiment



The CeC system





Main Beam Parameters for CeC Experiment

Parameter	Value
Species in RHIC	Au^{+79} ions, 40 GeV/u
Relativistic factor	42.96
Number of particles in bucket	10^9
Electron energy	21.95 MeV
Charge per e-bunch	0.5-5 nC
Rep-rate	78.17 kHz
Average e-beam current	0.39 mA
Electron beam power	8.6 kW

✓ CeC experiment parameters are well within revised RHIC Accelerator Safety Envelope (ASE)

Accelerator is under low power test

- All CeC systems are installed. The system went through Internal Readiness Review (IRR) in early December 2015, Accelerator Readiness Review (ARR) in early March 2016.
- <u>We received permission for low power (< 1W) beam test</u>
- Magnet installation and wiring is completed.
- Cryogenic system is fully operational and provide adequate cooling to 4K and 2K SRF systems
- Injection (SRF gun) system was tested in July 2015 at low power

Department of Energy
Brookhaven Site Office
P.O. Box 5000
Upton, New York 11973

MAR - 8 2016

Ms. Gail Mattson
Brookhaven Science Associates, LLC
Brookhaven National Laboratory
Upton, New York 11973

Dear Ms. Mattson:

SUBJECT: APPROVAL OF THE ACCELERATOR EXEMPTION REQUEST FOR THE COHERENT ELECTRON COOLING LOW POWER TEST

Reference: Letter from G. Mattson, BSA, to F. Crescenzo, SC-BHSO, Subject: Request BHSO Approval of 1) Revised RHIC Accelerator Safety Envelope (ASE), Basis in USI: Safety Analysis for Coherent Electron Cooling Proof of Principle (CeC PoP) Experiment at RHIC and 2) Low-Power Exemption, Basis in USI: Low Power Test Exemption for Coherent Electron Cooling Proof of Principle (CeC PoP) Experiment at RHIC.

The Department of Energy (DOE) Brookhaven Site Office has reviewed your request for a temporary exemption from the requirements of DOE O 420.2C, Safety of Accelerator Facilities, in order to perform a low power test of the CeC PoP Experiment. Based on our review and the subsequent completion of all actions required by the Internal Readiness Review (IRR) team, low power testing of the CeC is approved. The testing can commence under the limits established by the requirements specified in the Collider-Accelerator Department (CAD) Operations Procedure Manual (OPM) 2.5.2.2, Testing Safety Envelope Procedure for CeC PoP Experiment. The low power testing is expected to last until all pre-start actions from the Commissioning Accelerator Readiness Review (ARR) have been completed and commissioning of CeC PoP at full power begins. Therefore, the low power test exemption will expire at the end of this RHIC run or July 1, 2016, whichever occurs first.

If you have any questions, please contact Patrick Sullivan, of my staff, at extension 4092.

Sincerely,

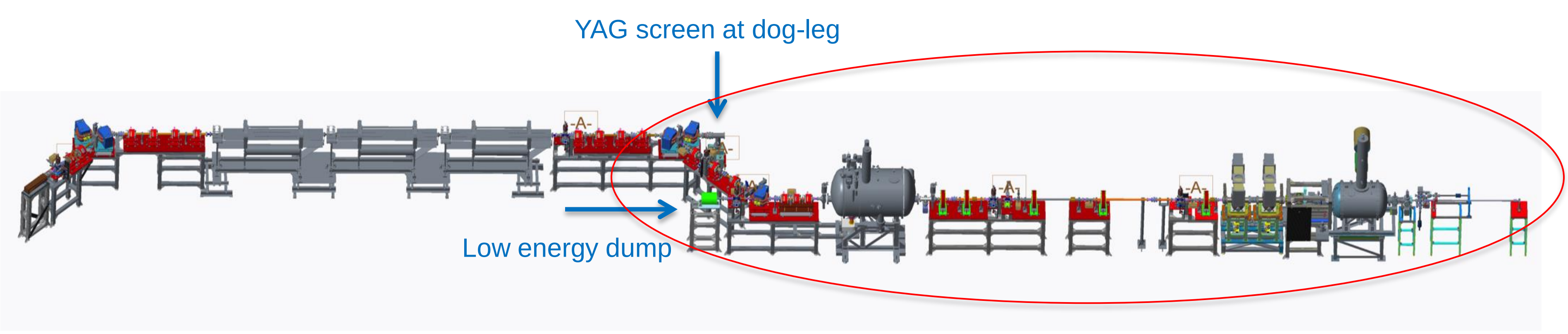
Frank J. Crescenzo
Site Manager

cc: M. Dikeakos, SC-BHSO
R. Gordon, SC-BHSO
P. Sullivan, SC-BHSO
E. Lessard, BSA
V. Litvinenko, BSA
T. Roser, BSA
C. Schaefer, BSA

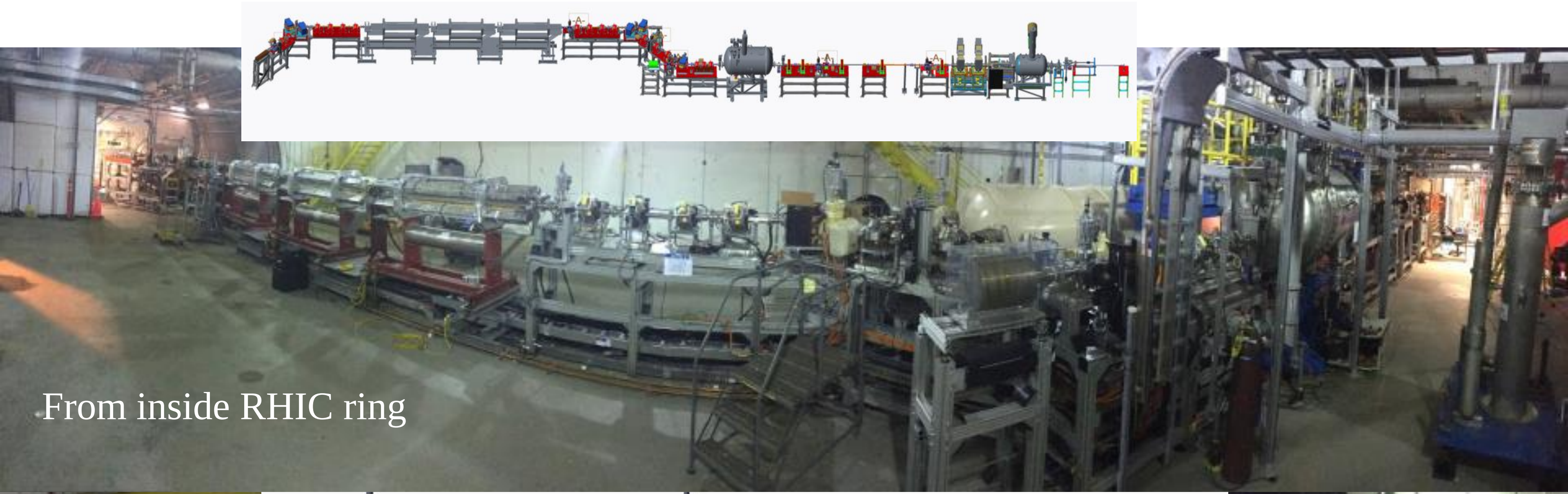
- **SRF gun is re-commissioned in both photo-injector and dark current modes. Demonstrated ~1.8 MV in pulsed ~1.5 MV in CW modes – sufficient for initial operation**.
- **704 MHz SRF linac is undergoing conditioning starting March 25 – reached ~15 MV in pulsed mode and ~ 9.5 MV in CW mode. Just started…**
- Energy of the beam was calibrated using 45-degree dog-leg magnet

Accelerator is under low power test (continued)

- **Low power beam was propagated to the low-power beam dump and to the profile monitor in the dog-leg.**
- We understand very well the level of dark current. Cold emission is under 100 to 200 nA
- The common section with RHIC – the Coherent electron cooling section - with 4 dipoles, 8 quadruples, 3 helical wiggles, trims and diagnostics is completed. Hadron beams are circulating through it.
- Many of sub-systems : vacuum, water, cryo, RF, PS, diagnostics had been tested to a degree or commissioned
- Anticipate to receive permission for commissioning in mid-to-late April



Panoramic views

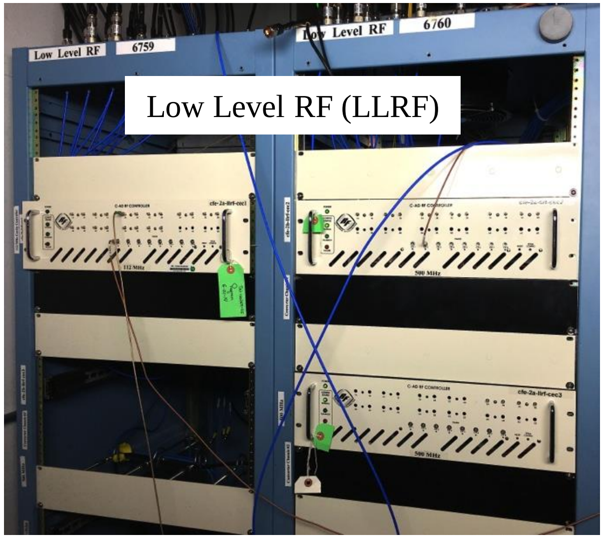


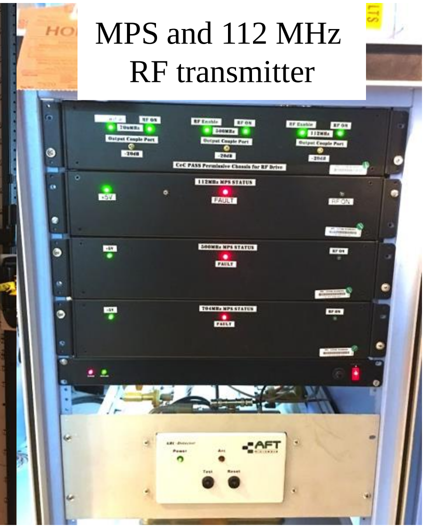
From inside RHIC ring

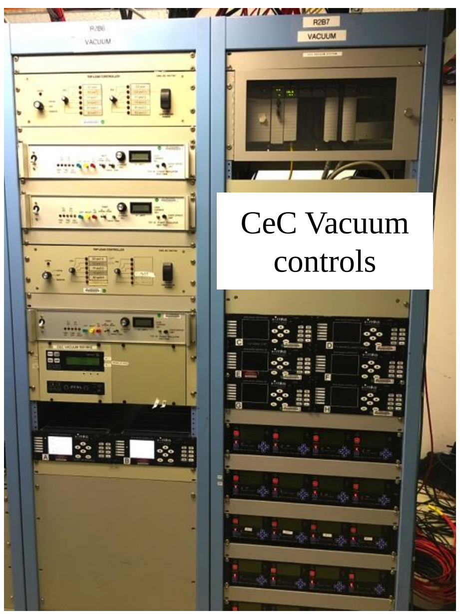
All CeC systems are installed

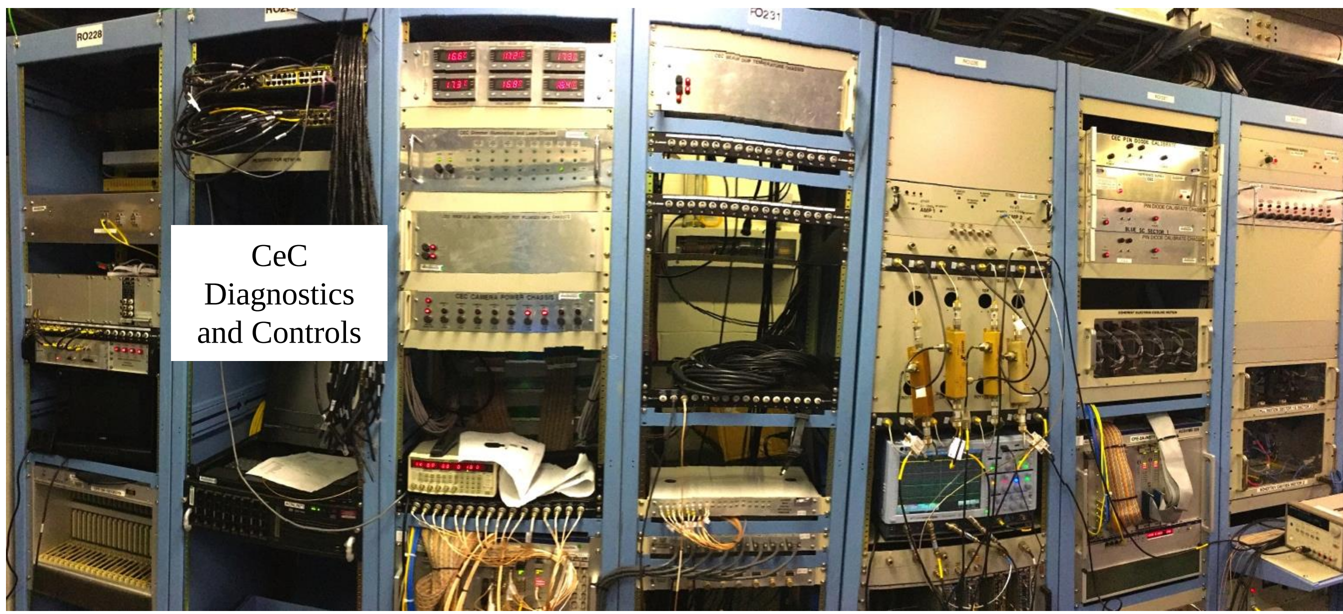
From outside RHIC ring

Some of CeC electronics



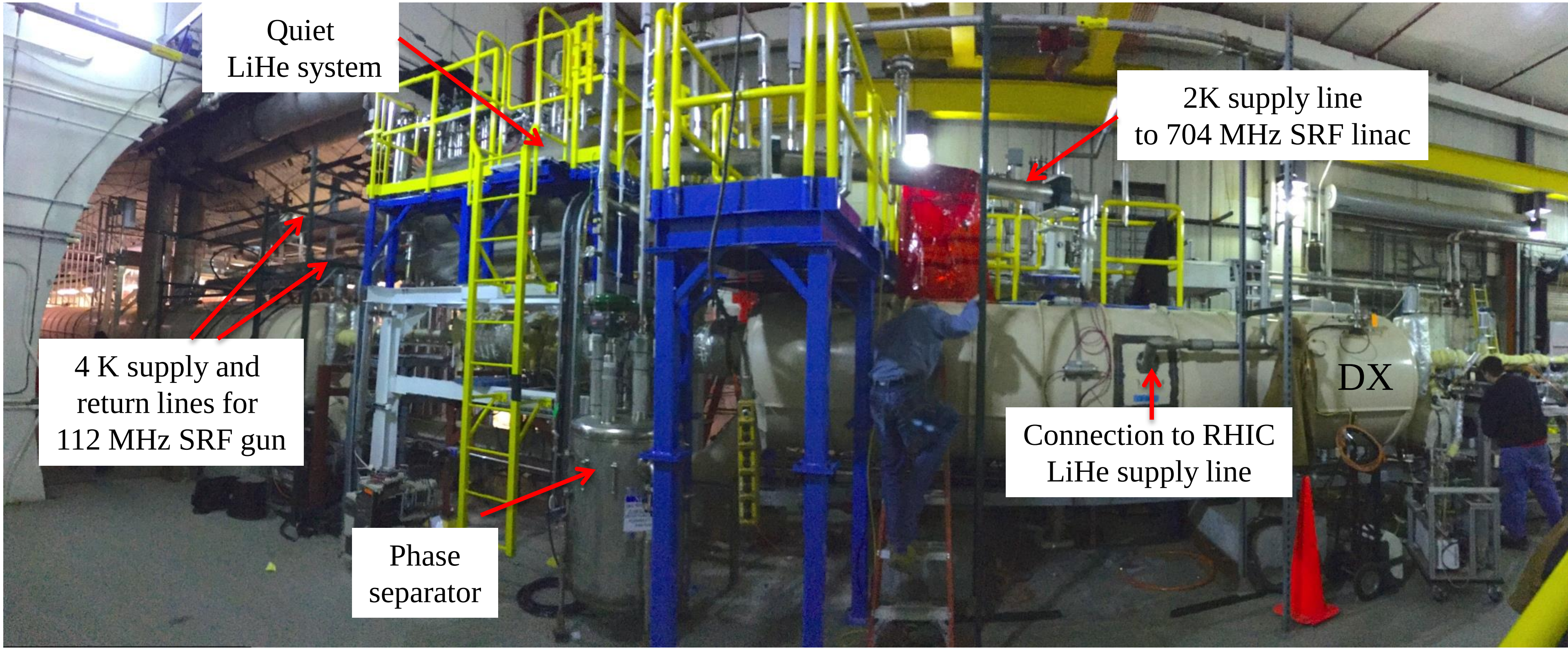






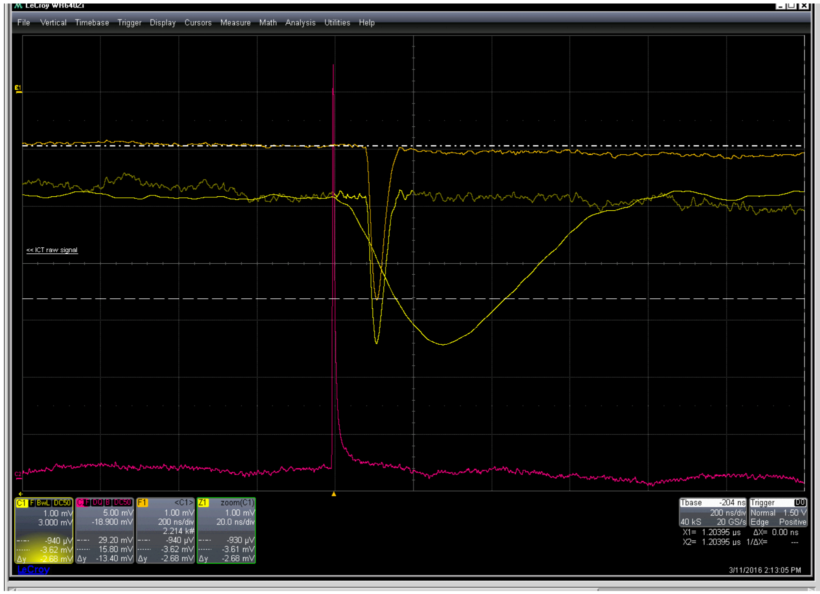
✓ All the electronics for the system are in place.

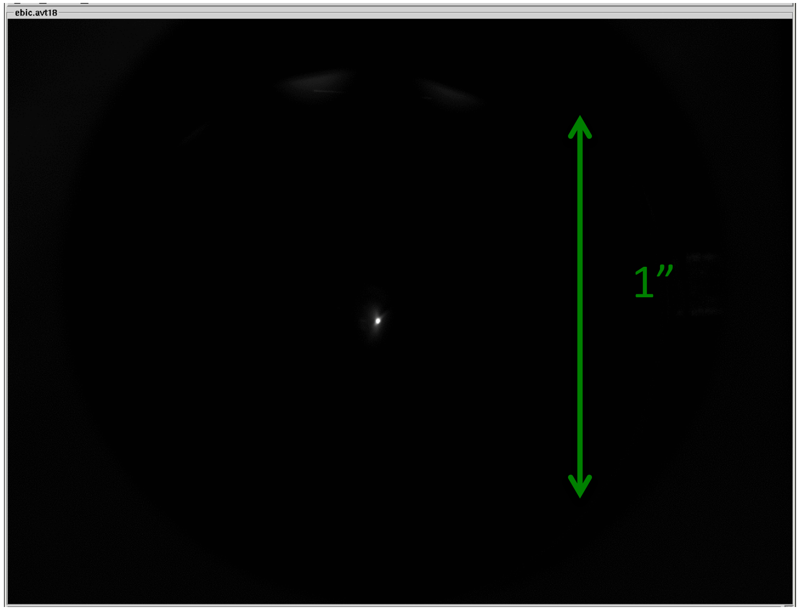
CeC cryo-system at IP2

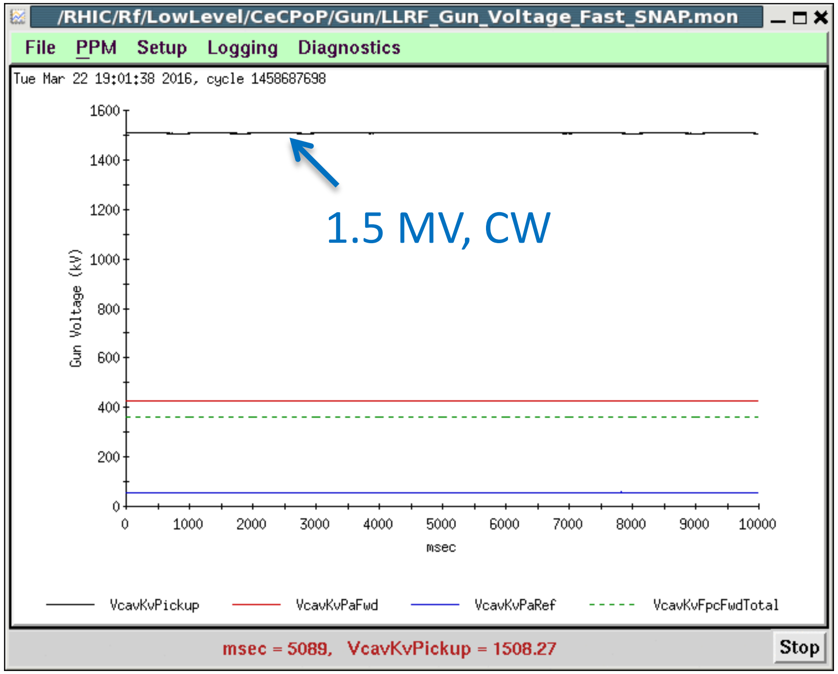


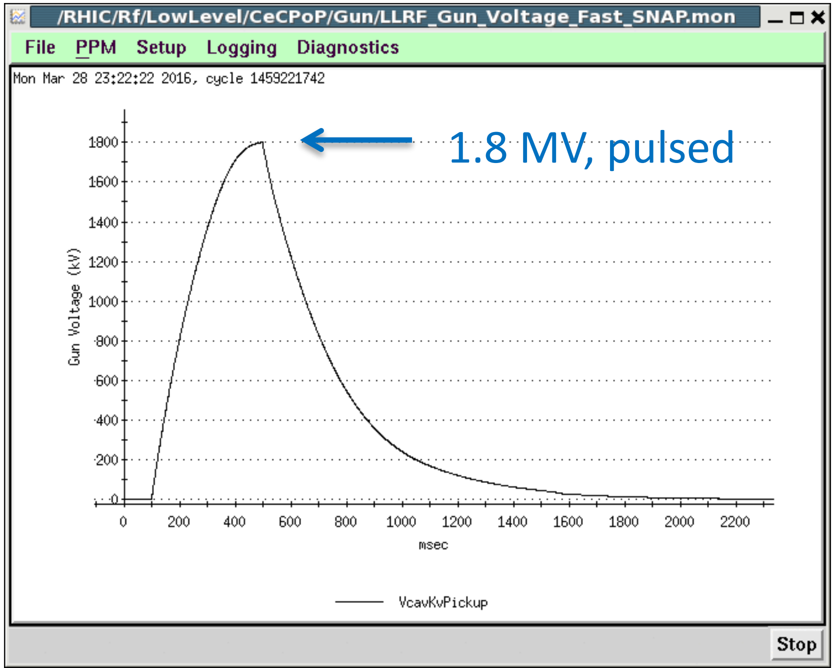
✓ Cryogenic system is fully operational and provide adequate cooling to 4K and 2K SRF systems

First photo-electrons in 2016 (March 10th)



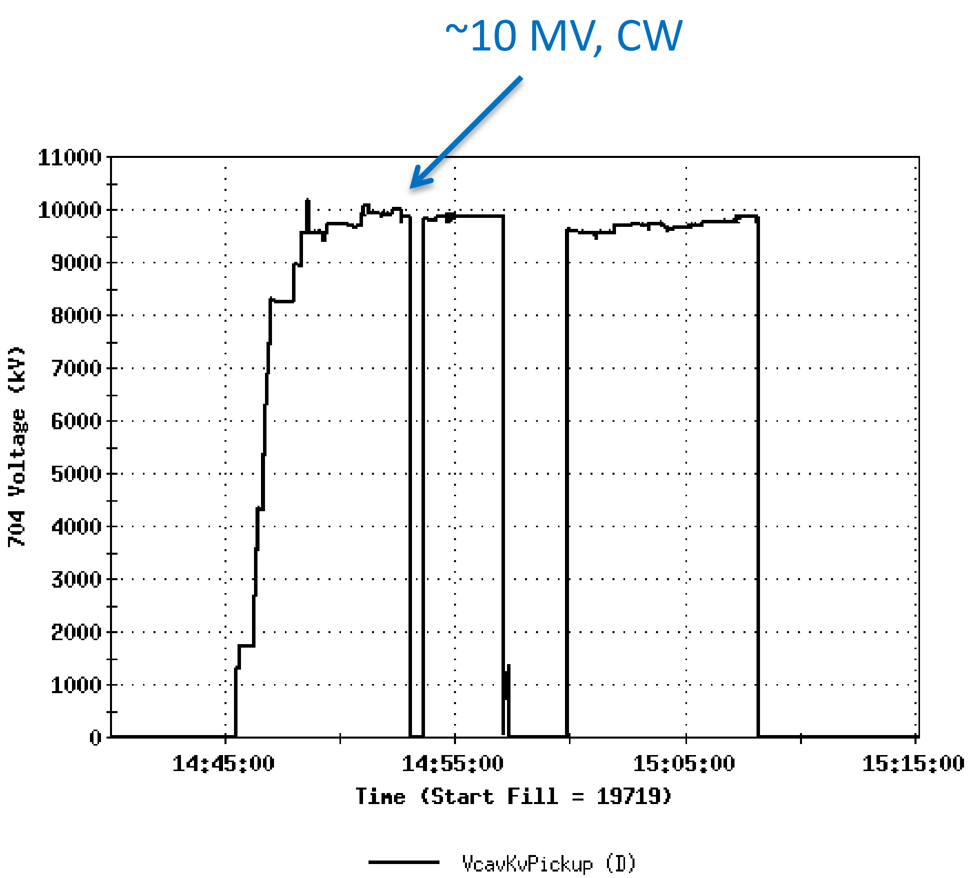


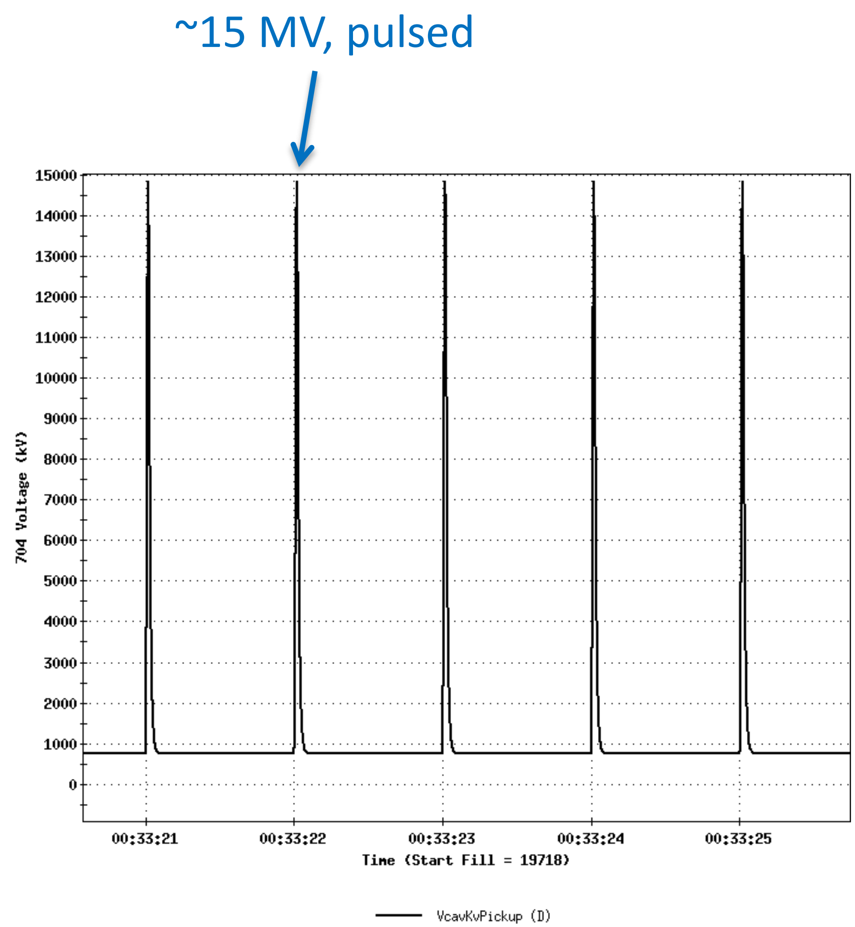




Main SRF linac: just started conditioning

✓ 704 MHz Cavity Conditioning Status as of March 31st, 2016





✓ **The required voltage is 20 MV and we are half way there.**

Main steps for CeC PoP

1. Finish installation of CeC PoP system into IP2
2. Developing RHIC ramp with proper beam envelope (beta*) in IP2
3. Developing RHIC ramp for CeC PoP experiment
4. CeC Accelerator Readiness Review (ARR)
5. *Conditioning of CeC RF system (112 MHz, 500 MHz & 704 MHz): design voltage, synchronized to RHIC beam, full control of voltage and phase*
6. *Re-commission the SRF gun, 500 MHz bunching cavities and accelerate beam to 20 MeV and beam power < 1W*
7. *Measure beam parameters (charge, emittance, peak current, energy spread…)*
8. Increase beam power 10x. follow by radiation surveys (and fault studies <10 W)
9. Propagate full power 20 MeV e-beam to the beam dump, match the beam into FEL
10. Commission IR FEL diagnostics and demonstrate FEL amplification
11. **Complete parasitic operations and start CeC dedicated operations**
12. Co-propagate, align and synchronize electron and ion beams
13. Match relativistic factors (velocities) of hadron and electron beams
14. Observe amplification of the density modulation
15. Attempt to observe local cooling

Alternative hadron cooling for nominal design

1. We are considering untested Coherent electron Cooling as a high risk item and are looking for possible already tested alternatives
2. RF stochastic cooling is not fast enough for eRHIC cooling challenges.

Parameters:	Linac-ring with e-cooling:			Ring-ring baseline:		
Hadrons per bunch, E11	2	2		3	3	3
Number of bunches	120	120		360	360	360
A	1	1		1	1	1
Z	1	1		1	1	1
Energy, GeV/n	50	250		50	100	250
gamma factor	53.289	266.447		53.289	106.579	266.447
beta-factor	1.000	1.000		1.000	1.000	1.000
eta-factor	1.46E-03	1.80E-03		1.46E-03	1.73E-03	1.80E-03
Longit.bunch area, eVs	1.6	1.6		0.32	0.66	1.6
RF harmonic	2520	2520		2520	2520	2520
RF frequency, MHz	197.020	197.053		197.020	197.046	197.053
RF voltage, MV	9	6		0.48	1.1	3
rms bunch length, cm	21.03	16.40		19.57	20.02	19.50
sigma_dp/p, E-4	24.20	6.21		5.20	5.24	5.22
Norm.transverse emittance,E-6,m	0.5	0.5		2.5	2.5	2.5
Unnormalized rms emittace, E-9m	9.38	1.88		46.92	23.46	9.38
IBS long (min)	614.00	99.40		21.5	60.20	246.60
IBS trans (min)	45.10	20.80		171.4	223.80	364.20

Most difficult for electron cooling due to high energy

3. For nominal LR design, magnetized electron cooling was selected as a technique which could, in principle, provide cooling times under 1 hour – sufficient to sustain modest luminosity in eRHIC

Alexei Fedotov

Electron cooling concept

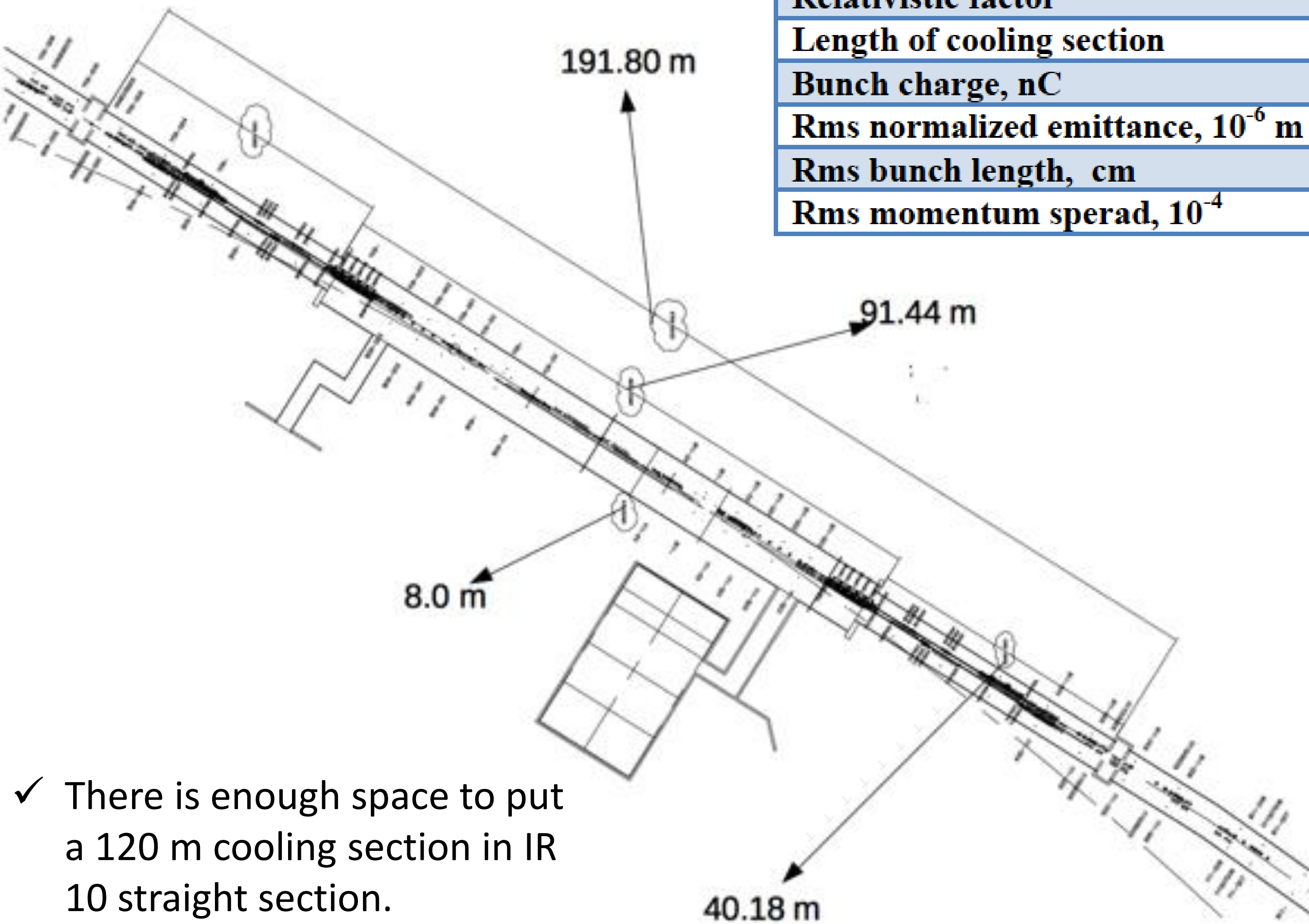
- Electron cooling process is thermalization of two component plasma: hot ions, cold electrons – ions are cooled

- There are two types of electron cooling:
  - ❑ Non-magnetized electron cooling
  - ❑ Magnetized electron cooling

- **For nominal LR design, the current primary consideration is magnetized electron cooling**

Parameters for eRHIC magnetized electron cooling

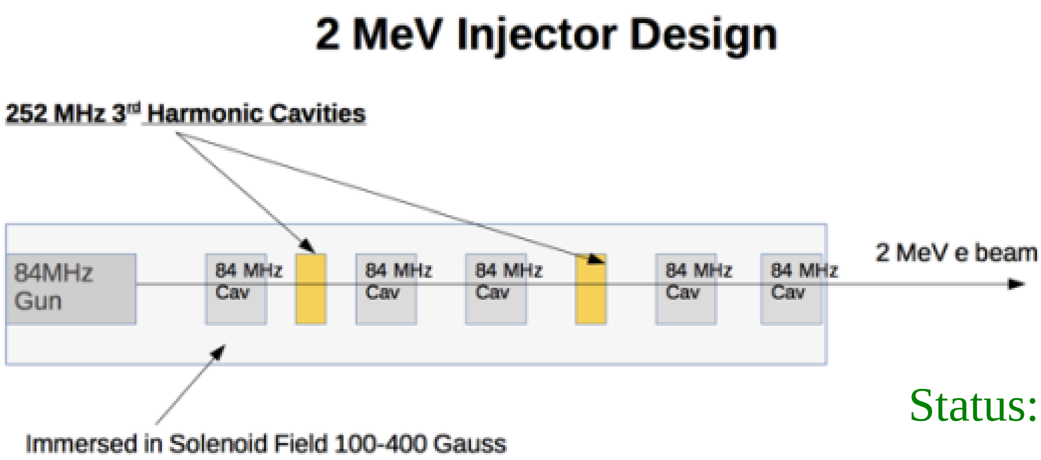
Relativistic factor	266
Length of cooling section	120
Bunch charge, nC	100
Rms normalized emittance, 10^{-6} m	40
Rms bunch length, cm	16
Rms momentum sperad, 10^{-4}	5

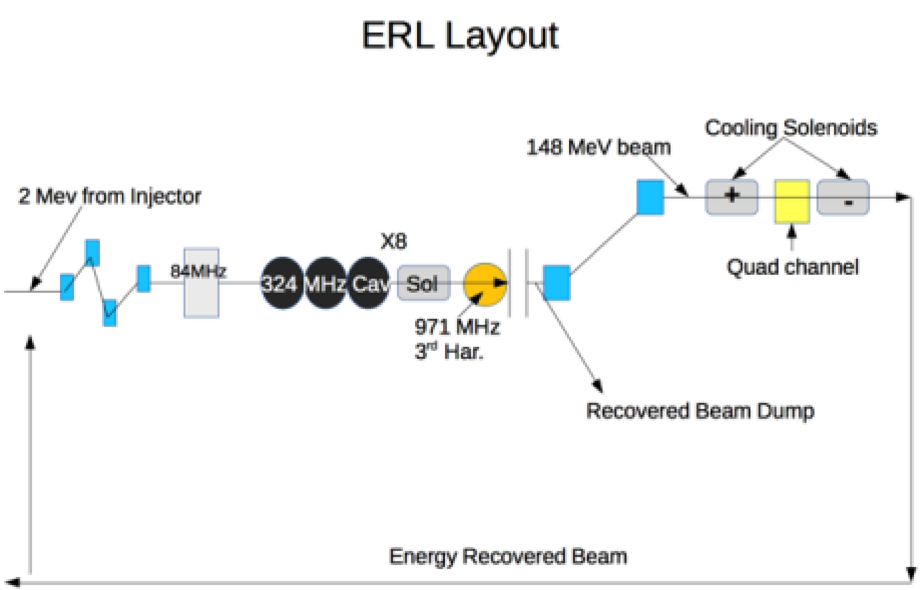


- ✓ There is enough space to put a 120 m cooling section in IR 10 straight section.

Status of magnetized electron cooling studies

Erdong Wang
Vahid Ranjbar





Status:

- Solenoid design is in advanced stage
- Simulations of the 2 MeV injector are completed
- ERL simulations are in progress: emittance is reduced to 60 mm mrad, but energy spread is still at 0.3% level compared with required 0.05%
- Cooling simulation is on the way

Summary: CeC PoP experiment

- ✓ CeC proof-of-principle system is in place and we started low power tests.
- ✓ We are ready to start commissioning after closing the remaining action items and receiving approval from DoE
- ✓ Good start but a lot of work ahead.
- ✓ We are preparing plan for next step: 3D cooling tests

Summary: Alternative e-cooling

- ✓ Magnetized cooling is chosen as an alternative which can provide some hadron cooling at store energy
- ✓ While not a new concept, it required expensive and complex accelerator (high energy ERL with 1 A average current)
- ✓ Electron beam parameters at the cooling section are also challenging: 100 nC per bunch of magnetized beam with relatively low energy spread and emittance
- ✓ Critical components such as RF gun with grid (immersed in the magnetic field and generating 100 nC per bunch, 1 A CW beam) and 120 m solenoid with required field quality are risk items and would need dedicated R&D

Backup Slides

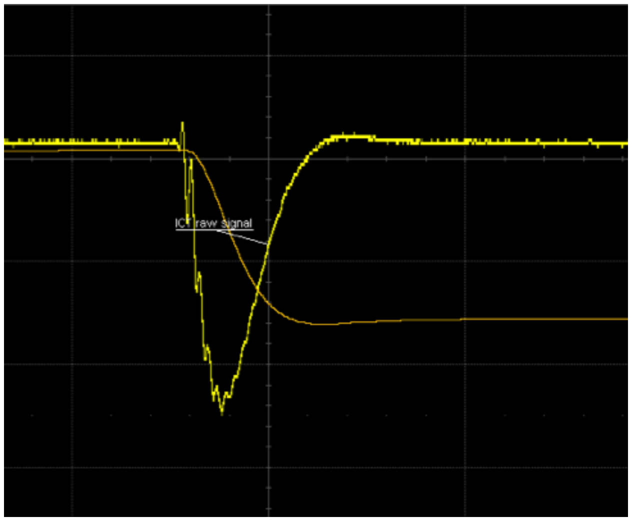
Parameters for eRHIC CeC system

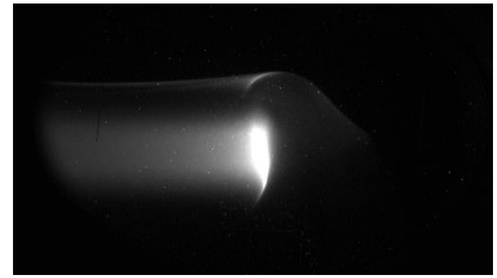
Hadron beam parameters			
Beam energy, GeV	250	Particles per bunch	2×10^{11}
ε_n, mm-mrad	0.2	Full bunch length, nsec	0.2
Energy spread, RMS	10^{-4}		

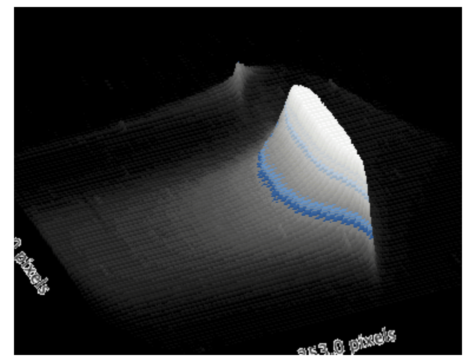
CeC system parameters			
Beam energy, MeV	136.2	Peak current, A	10
ε_n, mm-mrad	3	Full bunch length, nsec	0.5
Energy spread, RMS	3×10^{-4}	Modulator length, m	50
FEL wiggler length, m	24	Kicker length, m	25
Radiation wavelength, nm	422	Wiggler period, cm	3
Wiggler parameter, a_w	1	CeC bandwidth, Hz	4.4×10^{12}
Cooling time, hours	0.18		

First beam from 112 MHz gun – June 2015

- 1.6-1.7 MeV (kinetic energy) in CW mode
- Laser generated CW e-Beam with 3 nC @ 5 kHz
- 2 MeV in pulse mode
- 25 MV/m at photocathode







Milestones reported to DoE NP Q3 FY15

Demonstrating operation of 112 MHz SRF gun with 3 nC charge per bunch, 1.6 to 1.7 MeV kinetic energy in CW mode and above 2 MeV in pulsed mode.

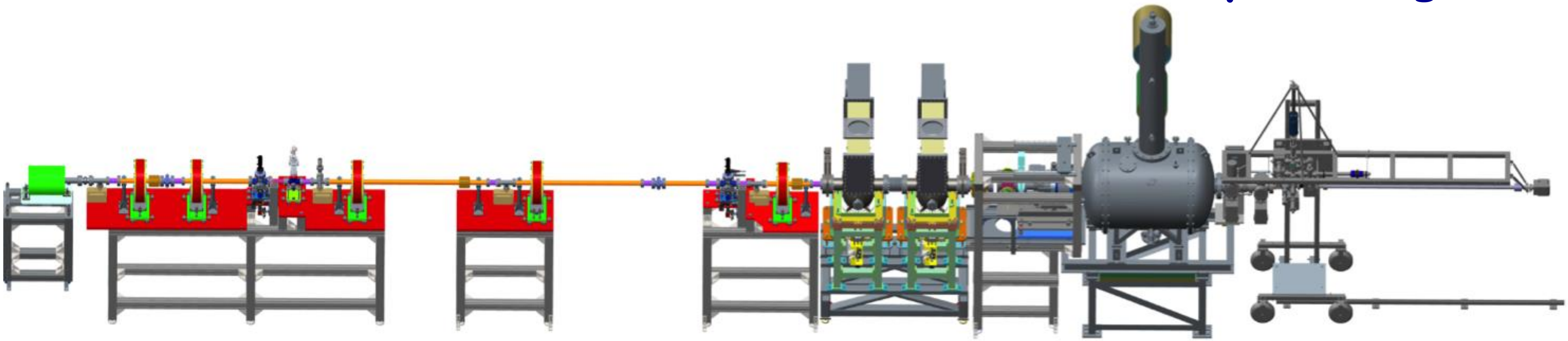
Production of high QE photocathodes for 112 MHz SRF gun.

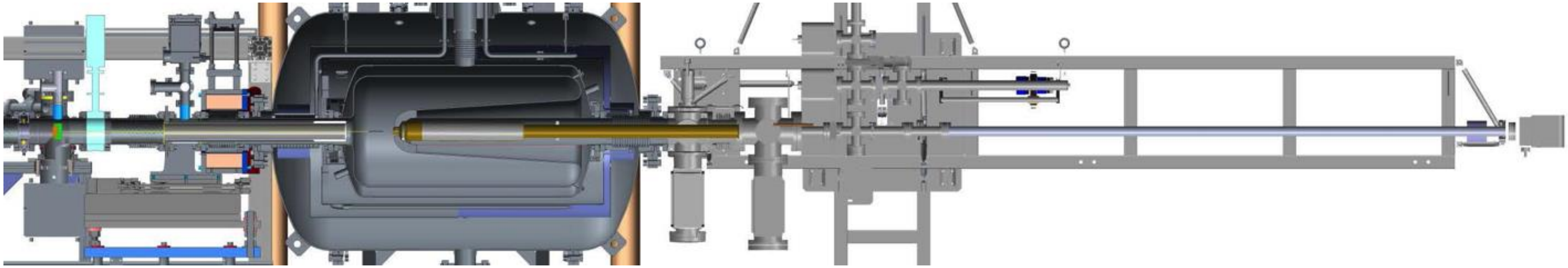
Receiving helical wiggler system for CeC PoP FEL amplifier

Completion of the 704 MHz SRF linac cryo-module at Niowave Inc.

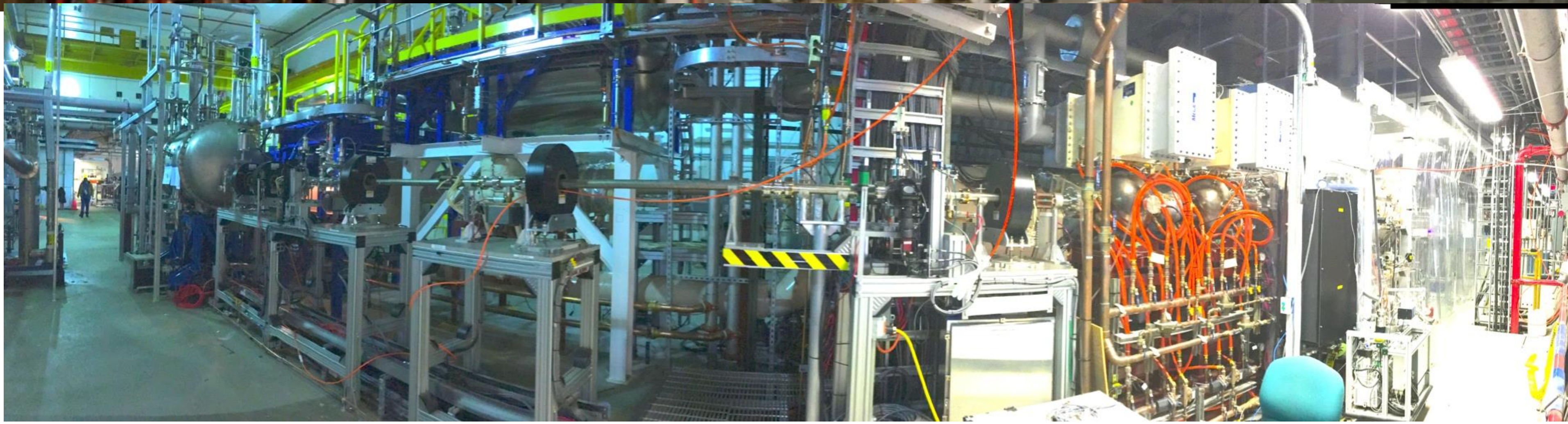
Completing the low energy transport beam line and its control system.

Phase 1 – Beamline installation and 112 MHz Cavity Testing





Panoramic views



CeC cryo pumps and compressor

Electron cooling for eRHIC

High-energy approximation (longitudinal ion velocities << transverse):

$$\tau_{cool} \propto \frac{A}{Z^2} \frac{\gamma^2}{4\pi r_p r_e n_e c \eta \Lambda_c} \left(\frac{\gamma \varepsilon_n}{\beta_c} \right)^{3/2}$$

$$\tau_{ibs,long.} \approx \frac{A^2}{Z^4} \frac{8\gamma^3 \beta^3 \varepsilon_n^{3/2} \sigma_p^2 \sigma_s}{N_i r_p^2 c \left\langle \beta_\perp^{1/2} \right\rangle \Lambda_{ibs}}$$

- Electron cooling becomes very slow for high energies
- Not as effective for protons as for heavy ions
- Colder ion beam are cooled faster: pre-cooling at low energies helps

- ❑ IBS for protons is significantly reduced compared to heavy ions
- ❑ IBS is reduced for longer proton bunches as assumed for nominal eRHIC scenarios (next slide)

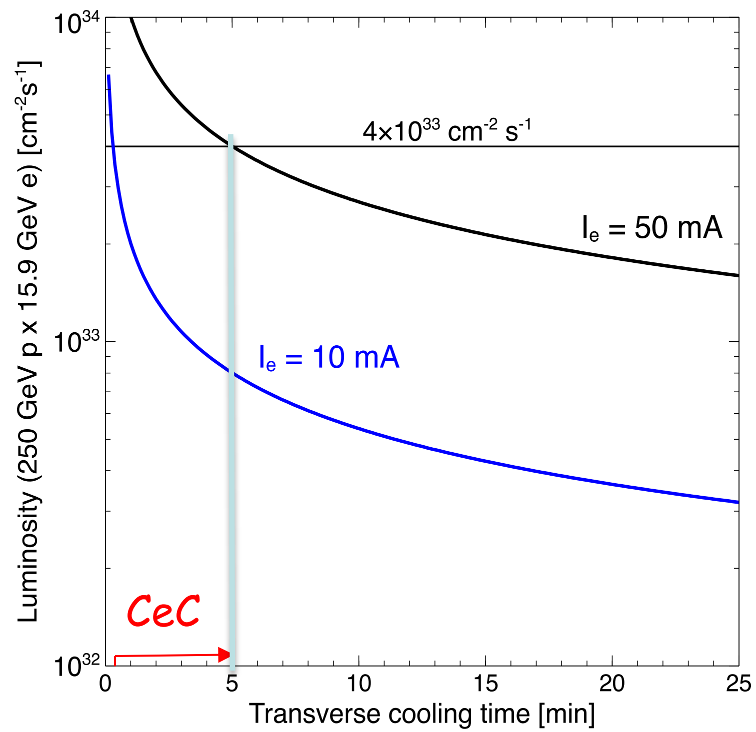
Alexei Fedotov

eRHIC luminosity vs cooling time

- At maximum luminosity (4×10^{33} $cm^{-2}\,s^{-1}$) the transverse IBS growth time of 250 GeV proton beam (3×10^{11} ppb, 0.2 mm, 5 cm bunch length) is about 20 seconds
- Only CeC with enhancements such as micro-bunching and with a 50mA, 125 MeV electron beam can reach this cooling time
- However, luminosity doesn't depend strongly on cooling time

$$L \propto t_{cool}^{-4/7}$$

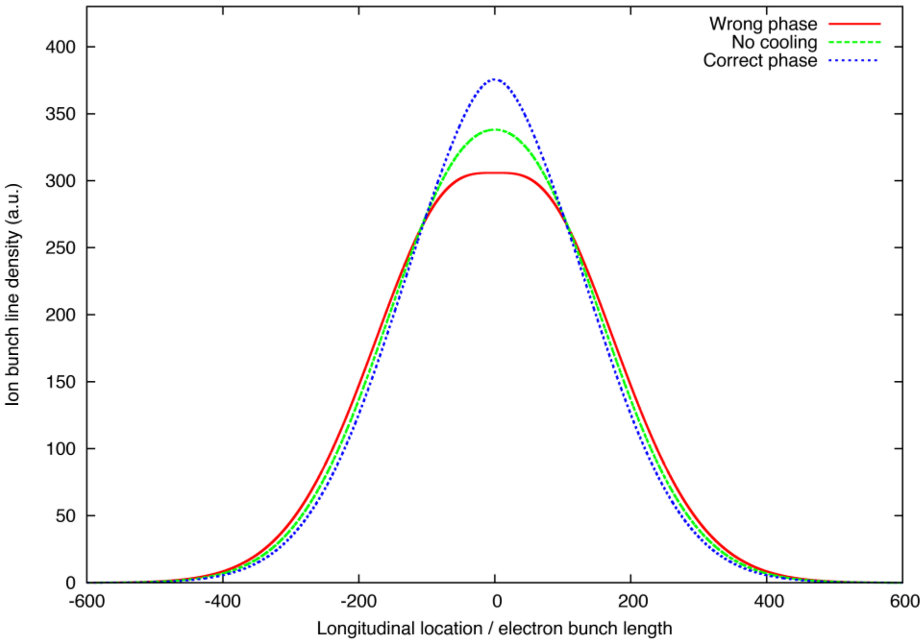
- Less efficient cooling up to 5 minute cooling time can be fully compensated with increased eRHIC electron current (50 mA)
- Demonstrating level of 5 minute cooling time is critical for eRHIC design



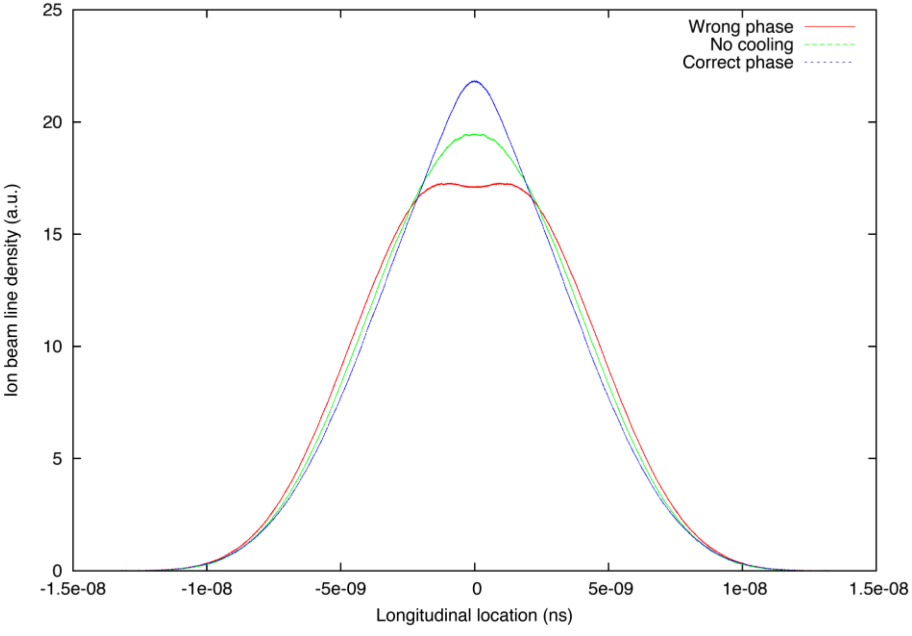
After 102 seconds of cooling ion bunch (with 1.6e8 bunch intensity), 3 nC electron bunch charge

Both macro-particle tracking and numerical solution of Fokker-Planck equation suggests that we should be able to see a ~10% difference in the peak current between cooled and un-cooled bunch within 102 seconds.

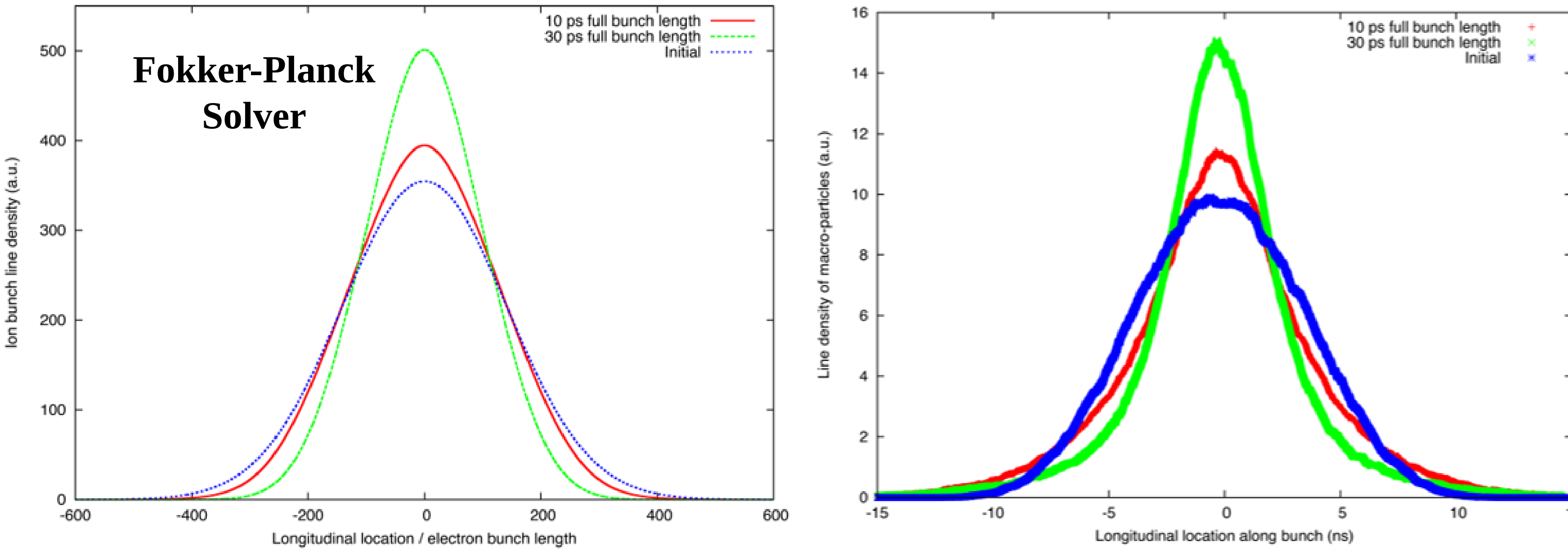
Fokker-Planck Solver



Macro-particle tracking



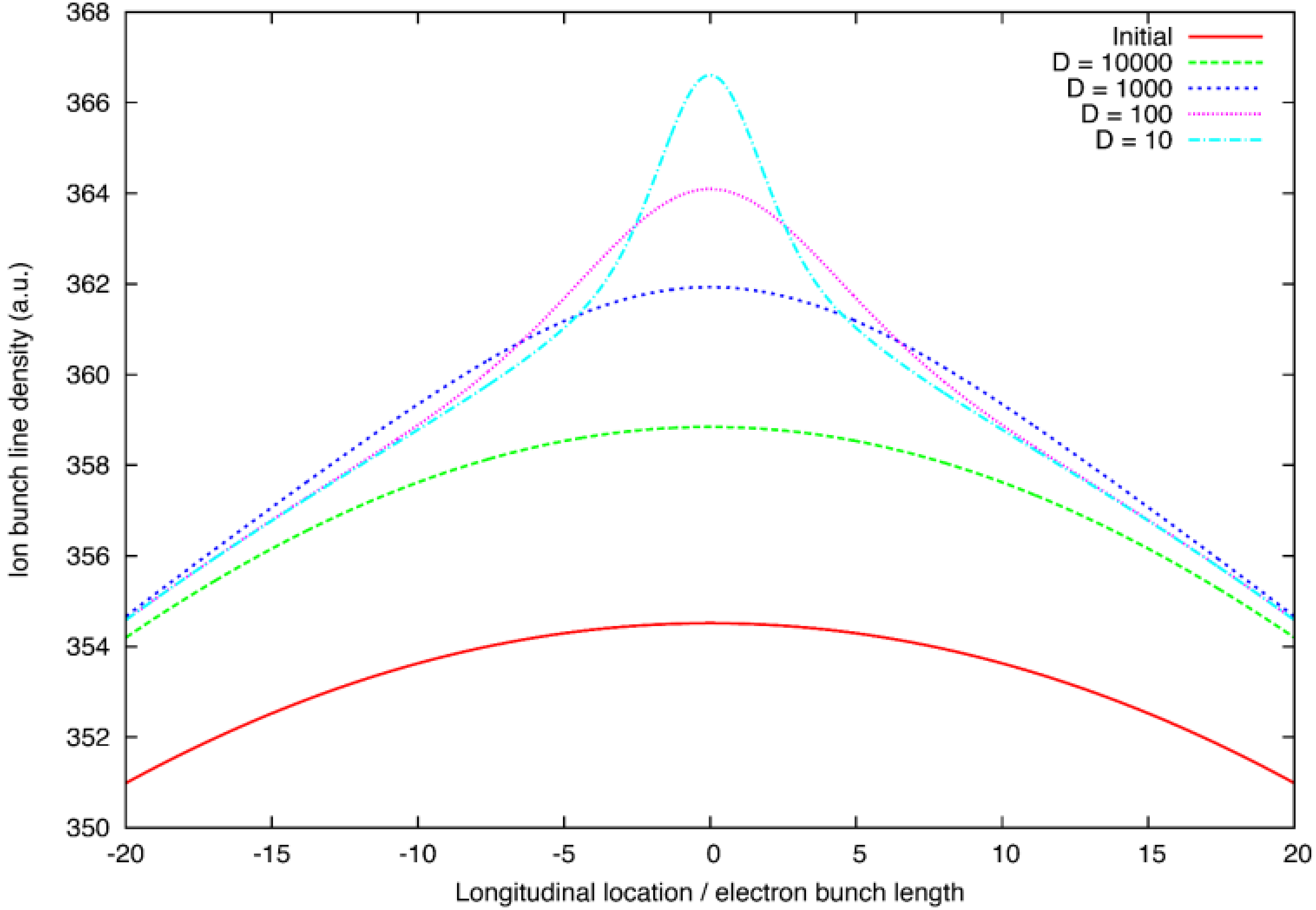
After 40 Minutes



(a) (b)

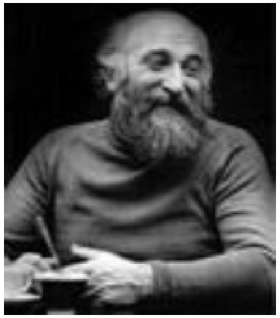
Figure 8: comparison of ion bunch line density obtained from Fokker-Planck solver, i.e. eq. (47) with that obtained from macro-particle tracking. (a) the ion bunch profile obtained from numerically solving Fokker-Planck equation; (b) the ion bunch profile obtained from macro-particle tracking. All snapshots (except for the initials) are taken at ~40 minutes after cooling starts ($\bar{t} = 856$). The IBS kick is 2.5×10^{-6} for the 10 ps case and 3×10^{-6} for the 30 ps case as calculated from the macro-particle tracking code. The bunch intensity is 1.6×10^{8}.

Effects from diffusion (IBS + diffusive kick induced by neighbour ions & electrons)

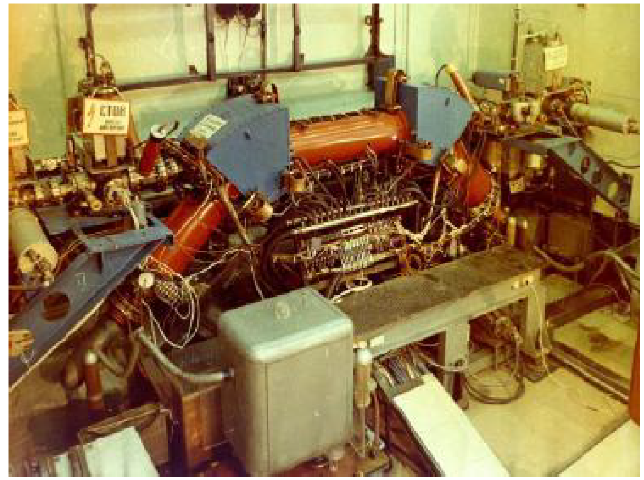


Electron coolers

Alexei Fedotov



Electron cooling was invented by G.I. Budker (INP, Novosibirsk, 1966)



First experimental cooling. NAP-M storage ring (Novosibirsk, 1974)

High Voltage DC coolers:

Standard electron coolers (1974-2015): 10's of coolers were constructed and successfully operated (low energies <300keV)– all DC electrostatic accelerators; all use strong magnetic field to confine electron beam (magnetized cooling). New 2MeV cooler under commissioning at COSY.

4MeV FNAL Recycler cooler: Pelletron electrostatic generator. Although weak magnetization was applied, effect of magnetic field on collisions was negligible; practically "non-magnetized" cooling.

RF acceleration (High Energy approach):

Low-Energy RHIC electron Cooler (LEReC): First RF-linac based electron cooler. Also without any magnetization (presently under construction at BNL).

Applications to high energy: Both magnetized and non-magnetized cooling approaches were studied in detail for RHIC-II electron cooler (BNL 2001-2007).

Magnetized cooling

1. Magnetized cooling: strong magnetic field in the cooling section limits transverse motion of electrons, so that transverse degree of freedom does not take part in the energy exchange. As a result, the efficiency of cooling is determined by the longitudinal velocity spread of electrons.

   In typical low-energy coolers longitudinal velocity spread of electrons is much smaller than transverse, thus allowing to cool ions to much smaller temperatures. Also, strong velocity anisotropy together with magnetic field leads to “fast cooling”.

2. Non-magnetized cooling: No magnetic field in the cooling section - standard collision process. Since there is no magnetic field to suppress transverse velocities of electrons, velocity spread of electrons should be comparable to the velocity spread of ions which needs to be cooled.